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PHOTOGRAPHIC TESTS OF RADIATION OF KEMPSTER DEVICE (C)

AUTHOR: Murray Cleare

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PHOTOGRAPHIC TESTS OF RADIATION OF KEMPSTER DEVICE

Introduction

On January 25 and 26, 1964, tests were run to determine the effects of the x-rays produced as a by-product of the Kempster ionization device, on photographic films for use in a number of sub-systems that will be located in the Q-bay of a high performance article. Article #128 was used in the evaluation.

The article was placed on jacks so that the nose wheel could be retracted into its normal flight position. The mass of the nose wheel assembly should provide significant shielding for the Q-bay. The fuel was drained from the number one fuel tank so that it did not provide shielding that normally would not be present during use of the Kempster system.

The ground-based simulation of the Kempster device radiation field was under the direction of Dr. Peter N. Wolfe, with technical assistance in the film and radiation effects by Mr. Murray Cleare.

Kempster Device Simulation

The Kempster device is to be installed in each chine of the craft near the wing fairings between fuselage stations #685 and #700. Electron guns will be installed on each side of the vehicle with the electron beams normal to the direction of flight and in a horizontal plane. At the operation altitude, the 150 Kev electron beams will form cones of ionization extending outward from the chines for a distance of approximately 300" (the maximum range of 150 Kev electrons in air at the design altitude).

As the electrons traverse the air, most of their energy is lost in excitation and ionization of the air. For electrons of 150 Kev and lower energy, the rate of energy loss is nearly inversely proportional to their velocity squared. The maximum ionization of the Kempster device, however, is not at the maximum range of the electrons (as indicated by the $\frac{1}{V^2}$ relation) because the relatively low mass electrons undergo multiple coulomb scattering so that the number of electrons decreases with distance from the source. The result of these two

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effects ($dE/d_x :: \frac{1}{V^2}$ and number-range relation) is that the maximum ionization per unit volume of air occurs at .3 to .4 of the maximum range of the electrons.*

A second form of energy loss, energy loss by radiation, is also present. This radiation, commonly called electron bremsstrahlung (or x-rays) is a result of elastic scattering of the electrons. The electron bremsstrahlung plays little or no part in the role for which the Kempster device is designed, but does provide a source of penetrating radiation that can adversely affect the performance of photographic systems in its vicinity.

In contrast to the ionization process in which the rate of ionization is proportioned to $\frac{1}{V^2}$ or 1/E (the electron energy), the efficiency of bremsstrahlung production is directly proportional to E for the electron energies of interest and also is proportional to the atomic number (Z) of the stopping media.

Ground based operation of the Kempster device can not spatially simulate operation at the design altitude because the range (in terms of distance) of the electrons is inversely proportional to the density of the air. At ground level, the bremsstrahlung would be produced in a small volume of air very near the electron gun while at the design altitude it would be produced throughout a volume extending outward some 300". The spatial distribution of the source will be of considerable significance considering the angle through which the radiation must penetrate the vehicle structure in reaching the photographic materials. The effective thickness of the shielding provided by the vehicle structure is relatively large for a source of radiation near the electron guns and decreases, on the average, with distance outward from the guns.

In addition, the energy lost by the electrons from both of the energy loss mechanisms reduces the average energy of the electrons as a function of range. Thus, the energy of the electrons and therefore their bremsstrahlung production efficiency and spectral energy decreases with distance from the electron gun.

To simulate the complex spatial bremsstrahlung field expected at the design altitude, exposures were made at a number of locations

*See J. Res. N.B.S., Vol. 65A, #2, March-April 1961

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with an x-ray machine. The x-ray tube location, exposure time, and applied kilo-voltage are shown in Table 1 and Fig. 1. In essence, the bremsstrahlung field was simulated by a multiplicity of discrete sources whose maximum energy was adjusted to simulate the expected maximum energy of the bremsstrahlung at that location. (The photographic effects of the simulated field were recorded on film positioned within the Q-bay during the exposure series.)

A source of uncertainty in the x-ray simulation arises from the differences in spectral composition of x-rays produced by a thin versus a thick electron target material. In the case of bremsstrahlung produced in air, the radiation from any location would result from electron interactions with a thin target of air. The x-ray spectrum produced would have nearly equal intensity at all energies up to that of the electrons. In contrast, the x-rays generated in an x-ray tube (thick target), are much "richer" in intensity at low energies because of the complete absorption of the electrons instead of only partial absorption as in the air target case. In addition, the x-ray production efficiency for the tungsten target of the x-ray tube is higher than that of an air target by the ratio of their atomic numbers.

The Kempster device is designed to operate at 150 Kev and 80 Ma beam current per electron gun. The x-ray exposures at each fractional range location on each side of the vehicle were made at 10 Ma with a total exposure time of 9 minutes. The x-rays produced by the 10 Ma beam current in the tungsten target of the x-ray tube are about equal in intensity to those produced by a 100 Ma beam current in a "thick" air target. (Z_W/Z air = 74/7.2 $\sim$ 10 X). Therefore, the nine-minute exposures at each location were equivalent to 11.25 minutes 100 Ma/80 Ma x 9 Min.) of simulated operation if the addition radiation at low energies from the thick target is ignored. Considering the filtering effects of the x-ray tube window, the mass of material between the x-ray tube and film, the spectral response of film (See Fig. 2) and the ionization chamber measurements made in the Q-bay during the series of exposures (see Table 2), we estimate that the effective exposure time for the simulation was about twice that of the above calculation or 22.5 minutes. The factor of two is used to compensate for the added intensity at low energies from the x-ray tube. Thus, we conclude that the photographic effects described in the following section should be considered a simulation of what can be expected in 22.5 minute of operation of the Kempster device at the design altitude of the aircraft. However, the finite, point representation of the extended, continuous source did produce "Summation"-radiographic exposures with more abrupt density changes than are

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expected during actual use. A far more diffuse, quasi-radiographic exposure is expected.

Photographic Effects Study

To record the bremsstrahlung field inside the Q-bay, 14" x 17" x-ray film, Kodak Industrial x-ray film, Type AA, (5533-774-40-4), was positioned as shown in Fig. 3 and 4. The films were taped together to form large sheets and hung from the ballast assembly used to simulate the Q-bay payload. X-ray film was used because its sensitivity to x-rays is greater than that of the aerial films ultimately to be used. Thus shorter simulating exposures could be used to achieve a useful photographic density than would be required had even the fast aerial film under consideration been used.

The x-ray spectral sensitivity of the Type AA film is, for all intents and purposes, the same as that of the aerial films of interest:
Kodak Panatomic-X Aerial Film (Estar Thin Base) Type No. 4400,
Kodak Plus X Aerial Film (Estar Thin Base) Type No. 4401,
Kodak Special Aerial Negative Film (Estar Thin Base), Type SO-206,
Kodak High Definition Aerial Film (Estar Thin Base) Type No. 4404.
This was ascertained by measuring the maximum to minimum spectral sensitivity ratios (i.e. the ratio of sensitivity to heavily filtered 50KVCP x-rays and radium gamma rays) of the x-ray and aerial films in question. Previous tests of many widely different films have shown that the "shape" of the spectral sensitivity curve, for practical purposes, is invariant. Variations in maximum-to-minimum spectral sensitivity ratio are reflected only as proportional changes along the curve. Also, the shape of the sensitometric or H&D curve does not vary significantly with the energy of the exposing radiation. Therefore, since the spectral sensitivity ratio of the Type AA is the same as that of the aerial films, their relative responses will be the same regardless of the energy of the exposing radiation.

Figure 5 shows the x-ray sensitometric characteristics of the Type AA film and the aerial films under consideration. These curves were produced by exposure to 50KVCP x-rays filtered with 1/2mm copper plus 1mm aluminum (i.e. heavy filtration). The exposure to this radiation that is required to produce a particular density on the Type AA film can be read directly from the curve. The density produced on any of the aerial films resulting from a simular exposure, likewise, can be read directly from the curve. For any other energy

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or quality of radiation, these curves would have these same relative spacings because their relative spectral sensitivities are similar and only the exposure axis would be different, reflecting the change in their absolute sensitivity. (For example, an exposure to any reasonable energy of radiation that produced a density of 1.0 on the Type AA film would produce a density of 0.30 on the 4401 film.) Thus, the density produced on the aerial films by an exposure to radiation can be predicted from the density on the x-ray film without a knowledge of the energy of the exposing radiation.

For simplicity of presentation, all exposure values quoted in this report will refer to the exposure in terms of roentgens of heavily filtered 50KVCP x-rays, required to produce a density on the Type AA film equal to that produced by the radiation used in the experiment. The exposure values reported must not be considered as exposure dose measurements. They are reference values resulting from a complex "weighting" of the dose as function of energy by the spectral response of the film. This method of presentation also permits the results of this experiment to be applied to other films that may be of interest at some later date provided their relative spectral response is similar to that of the Type AA film.

Results

As to be expected, the "summation" radiograph images, showed a very complex exposure variation. However, the variations of exposure from area to area were not particularly large and, in general, varied by less then a factor of two. The areas of higher exposure represented an estimated 0 to 20% of the area of a film (14" x 17") and, in general, about 10%. The original x-ray films are on file. (No effort was made to reproduce these films for inclusion in this report due to the difficulties of making intelligible reduced copies of the 14" x 17" films.) Such relatively well defined areas of exposure would not be expected had the simulating exposures more closely approximated a continuous cone source of radiation as expected in ultimate use. However, it would not be prudent to simply assume that the exposure in these high exposure areas will be more diffuse and therefore less in the final usage. The superposition of the many structural parts between the source and the Q-bay may provide less shielding at angles other than those used in the test. Therefore, the shielding requirements are based upon the maximum exposures recorded in the test.

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Table 2 is a summary of the "equivalent" exposures determined from the density recorded on the x-ray films during the experiment.

The location of the films is shown in Figs. 3 & 4. The letters T, R, and L following the aft exposure films (A1, A2, etc.) indicate, respectively, that the exposures were determined from films receiving radiation from both, right only and left only simulating exposure series. The "localized exposure" column results from the evaluation of small high density areas of the films and is the total of the "uniform" overall fogging exposure and the localized high exposure. Where little variation of the "uniform" exposure occurred, minimum exposure levels were determined. Where "wedging" occurred across a film, maximum and minimum exposures were determined.

The exposures to the left and right side films resulted only from the simulating exposures made on their respective sides. The heavy ballast assembly prevented any attempt to record the effects of the left exposure series on the right side film and vice versa. These "cross-over" effects probably will not be too significant because the mass of the camera equipment will add some left to right shielding. But to be conservative, the right and left exposures were doubled for purposes of estimating the shielding required.

The range of recorded exposures throughout the Q-bay is surprisingly small. The maximum-to-minimum exposure variation found in this test is about a factor of 3; from approximately 30mR to 100mR. Had this range been greater, with higher localized area exposures, there would have been a compelling temptation to discount some of the very small "hot spots" seen on the films. But, as it turned out, it does not seem too unrealistic to simply base all shielding estimates on the maximum exposures observed. (Note that twice the max. exposure level observed on the side films is about 100mR, the max. level found on the aft films.)

Shielding Estimates

Assuming that the series of 9 min. x-ray exposures at each station is photographically equivalent to 22-1/2 minutes of operation of the Kempster system at design altitude and that a mission will require 4 hours operation of the system, unshielded photographic film in the Q-bay will receive an exposure equivalent to from 0.3 to 1R (i.e. -10X the observed range) of 50KVCP radiation. In Fig. 5, this exposure range is shown as the cross hatched region.

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An increase in density of 0.20 is not expected to seriously affect the contrast or graininess of aerial films. Under this assumption, the 4404 will not require radiation shielding. Within the accuracy of this experiment, the SO-206 can also be used without adding radiation shielding. It is estimated that under these assumed conditions, the background density will be increased by 0.24 at a maximum. The remaining films, the 4400 and the 4401 will require shielding to provide attenuations of factors of 5 and 20 respectively.

Using half value data from the National Bureau of Standards, Handbook 76, "Medical X-ray Protection Up to Three Million Volts" and ionization chamber reading made within the Q-bay by Dr. Wolf during the experiment (See Table 3 and Fig. 3), it is estimated that no more than 0.6mm of lead will be required for an attenuation factor of 5 nor more than 1.2mm for a factor of 20. This thickness would be required across the aft end of the Q-bay. Because of the angle of incidence of the radiation, only half this thickness would be required along the sides of the bay. It would be expected that no more than the aft 2/3 of the bay would require shielding to adequate "shadow" the Q-bay volume containing film. Also, unless film is to be located very near either hatch opening, we would not expect the hatches to require shielding. The intensity of scattered radiation reaching the bay through the unshielded hatches should be very small. The radiations of concern are essentially only those reaching the bay by line-of-sight.

Conclusions

Based upon what is believed to be a conservative estimate of the radiation effects to be expected from 4-hour operation of the Kempster devices during a reconnaissance mission, photographic systems located in the Q-bay will not require radiation shielding if 4404 Film is to be used. If SO-206 Film is to be used, no additional shielding is recommended but detectable fogging is anticipated. For the two faster films, shielding of the Q-bay is required. Probably less weight of shielding is required if the critical areas of the camera system are individually shielded though it may be simplier and more expedient to shield the bay itself. For systems using the 4400 Film, the aft bulkhead (or camera structures parallel to it) will require 0.6mm of lead shielding (1.5 pounds/$\mathcal{F}t^2$). The sides of the bay (or camera structures parallel to them) will require 0.3mm lead (0.75#/$\mathcal{F}$ t^2).

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The extent of the side walls requiring shielding can be determined from line-of-sight considerations and film versus shielding locations. Probably, no more than the aft 2/3 of the side walls need be shielded. For systems using 4401 Film, the shielding thickness requirements are doubled. In no case is shielding of access hatches expected to be necessary unless film remains for extended periods in unshadowed areas near the hatch openings.

Since the conclusions reached in this report are all based upon results obtained from a simulated Kempster radiation field, every effort should be made to check the validity of the simulation. Were we to speculate, we would expect that the shielding suggested in this report will be somewhat greater than actually required. We trust that flight tests of the Kempster system will be made as soon as possible with film dosimeter detectors positioned in the Q-bay.

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TABLE 1 - Exposure Conditions Used for Simulation

(All exposures were for 3 minutes at each location - 10Ma x-ray tube current)

Exposure Station	KVCP	Vertical Location*
1	150	0", 0", 0"
2	135	-10", 0, +10"
3	115	-20", 0, +20"
4	90	-30", 0, +30"
5	70	-33", 0, +33"
6	45	-36", 0, +36"

*As measured from the assumed horizontal center line of the electron beam.

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TABLE 2 - EQUIVALENT EXPOSURES IN mR*

Film Number	Localized Exposures	Minimum Exposures	Exposure E(max)	Wedging E(min)
R1	48	27	-	-
R2	34	26	-	-
R3	34	25	-	-
L1	41	27	-	-
L2	38	24	-	-
L3	34	29	-	-
A1T	67	-	49	45
A2T	93	-	82	41
A3T	52	-	41	31
A4T	98	-	85	41
A1R	-	-	24	17
A2R	-	-	34	17
A3R	31	-	27	21
A4R	45	-	34	21
A1L	34	-	24	21
A2L	34	-	38	21
A3L	-	-	23	21
A4L	-	-	38	21

*The exposure values listed in the table are those of 50KVCP x-rays filtered by 1/2mm copper and 1mm of aluminum that will produce the density recorded on the x-ray film.

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TABLE 3 - Exposure Rate Inside Q-Bay During Right-Side Exposure

(See Fig. 3 for placement of chamber)

Exposure Station	X-ray Exposure (KVCP)	m^R*/hr from exposure positions: Lower	Center	Upper
1	150		130	
2	135		145	
3	115	67	72	87
4	90	24	25	42
5	70		8	
6	45		.33	

*All exposure made with 10Ma x-ray tube current

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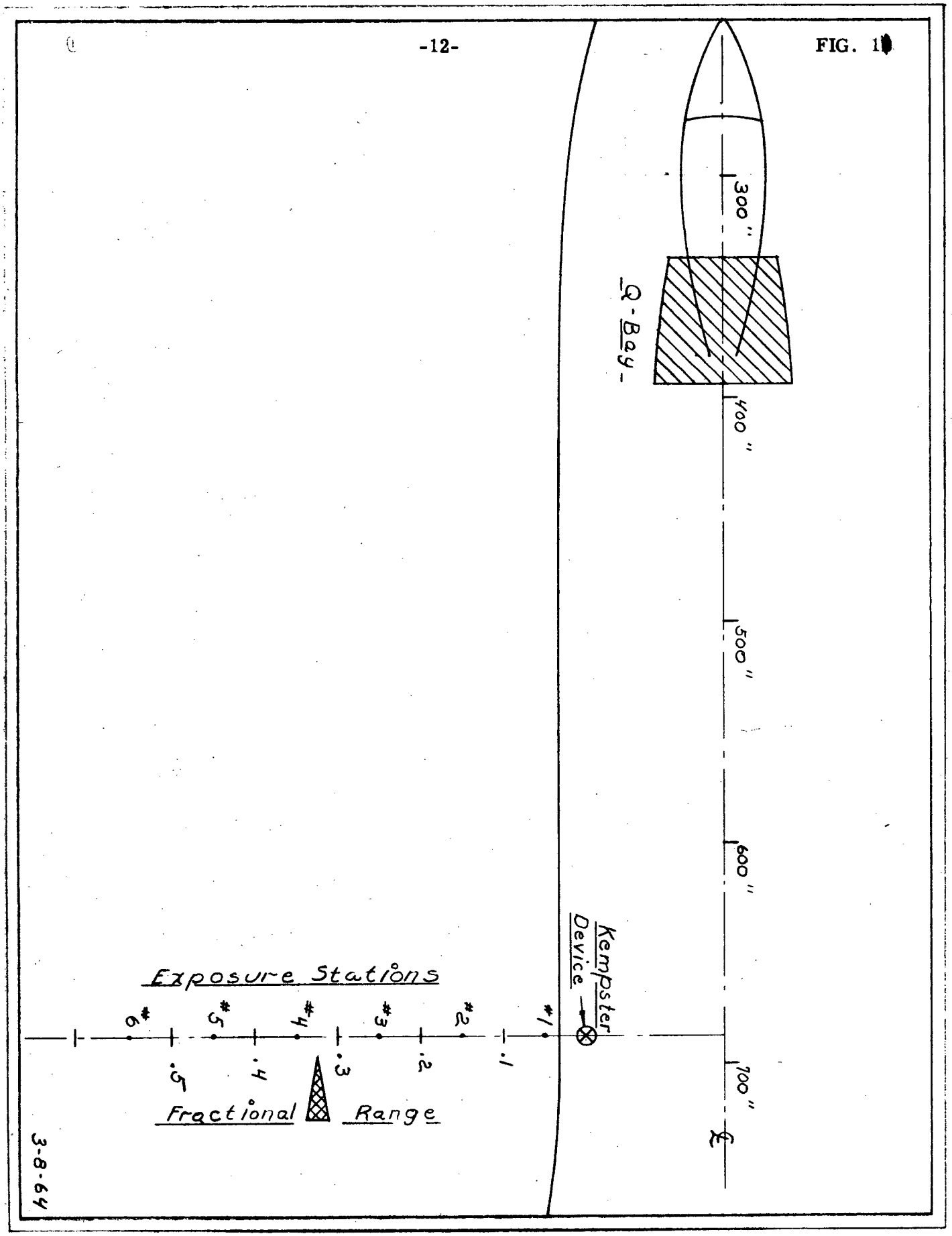
FIG. 1



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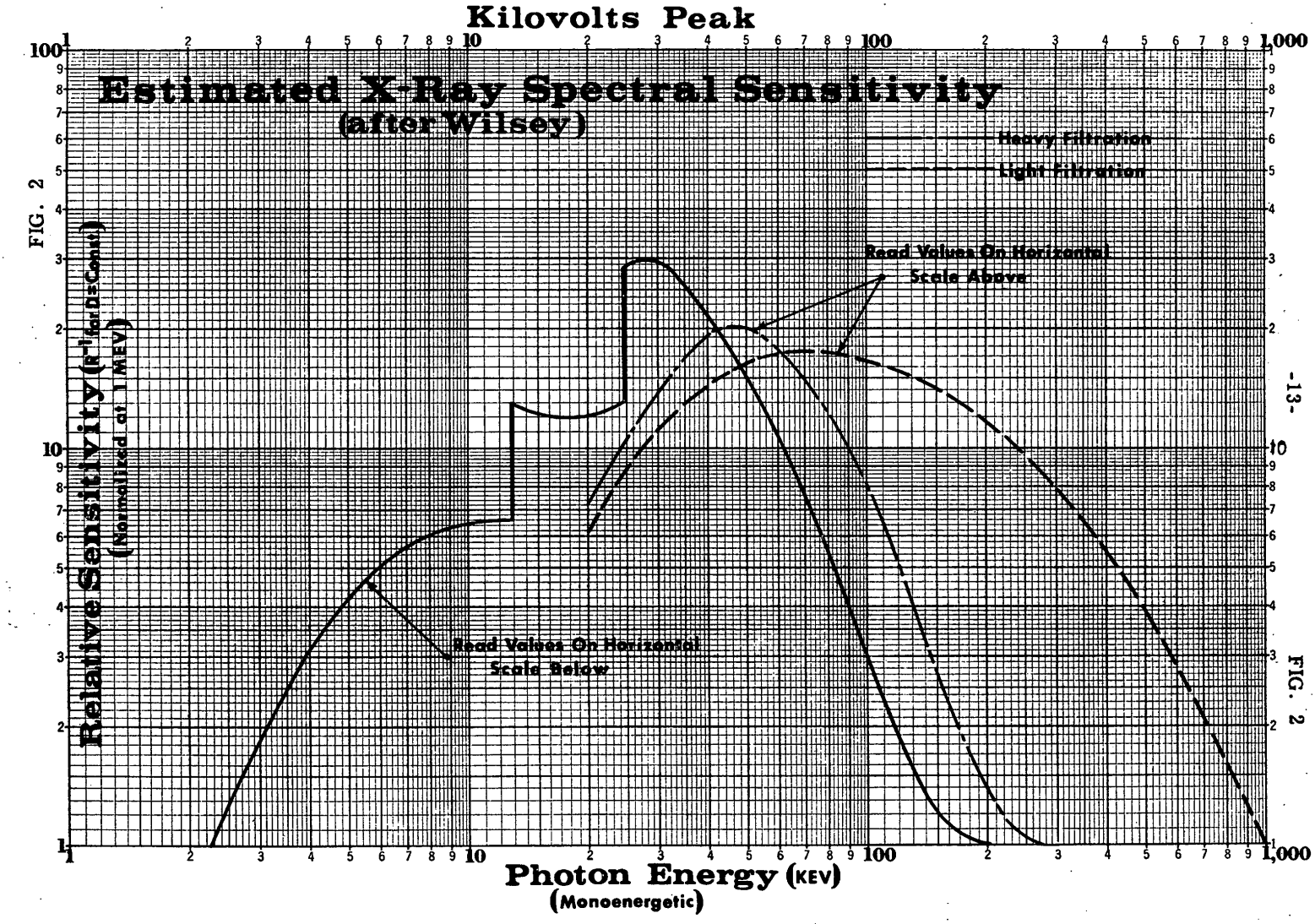

FIG. 2

FIG. 2

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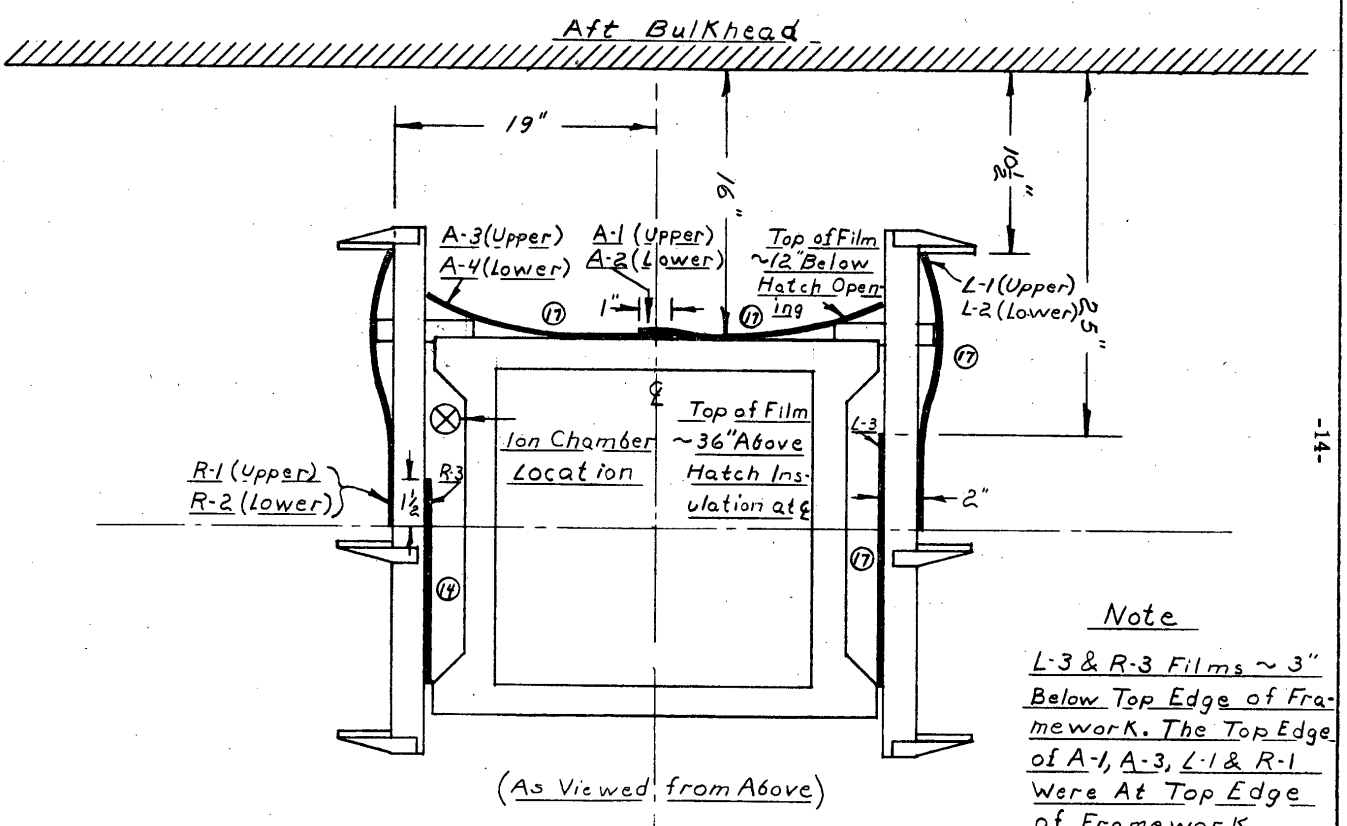

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FIG. 3

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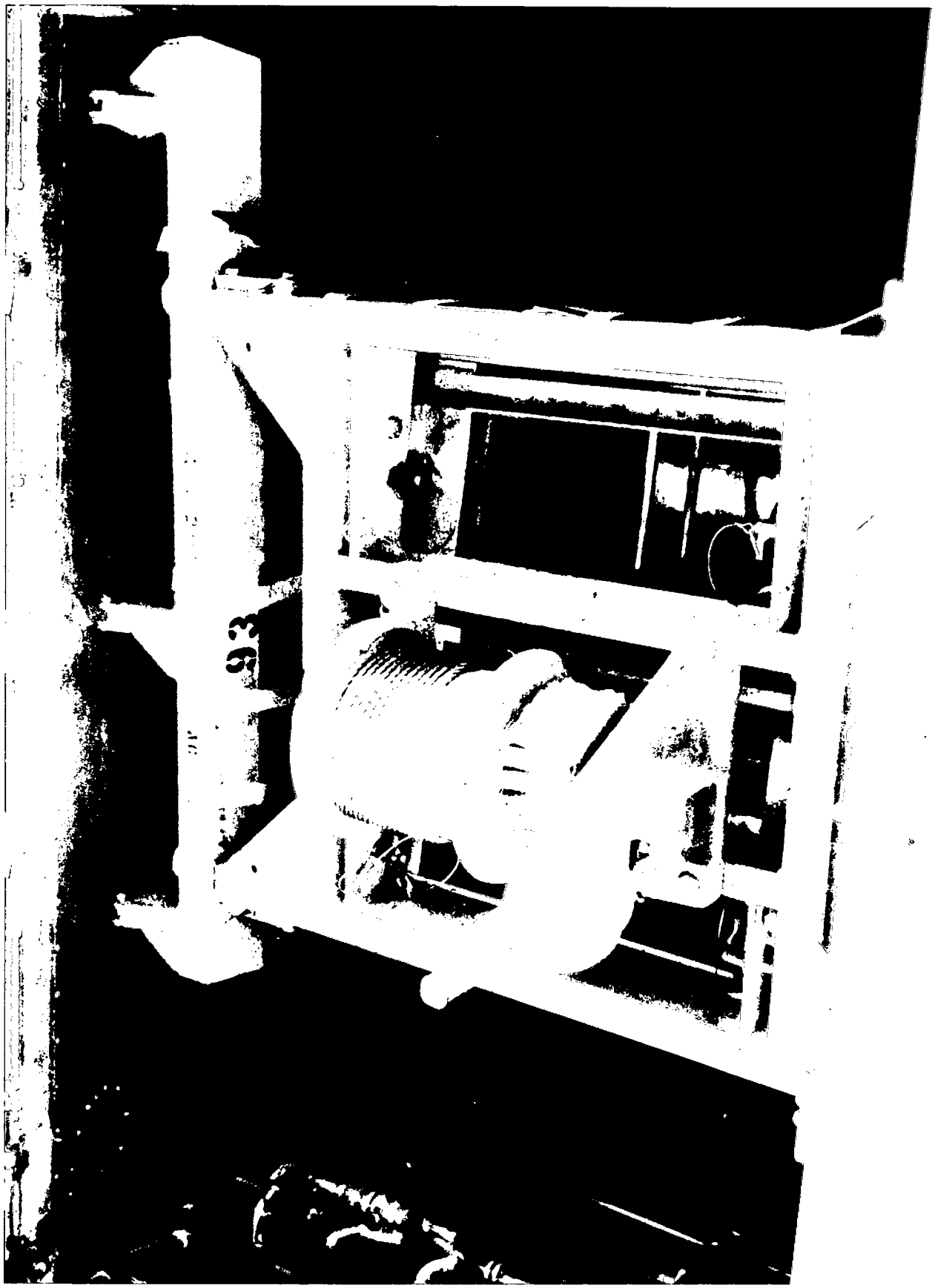
Figure 4



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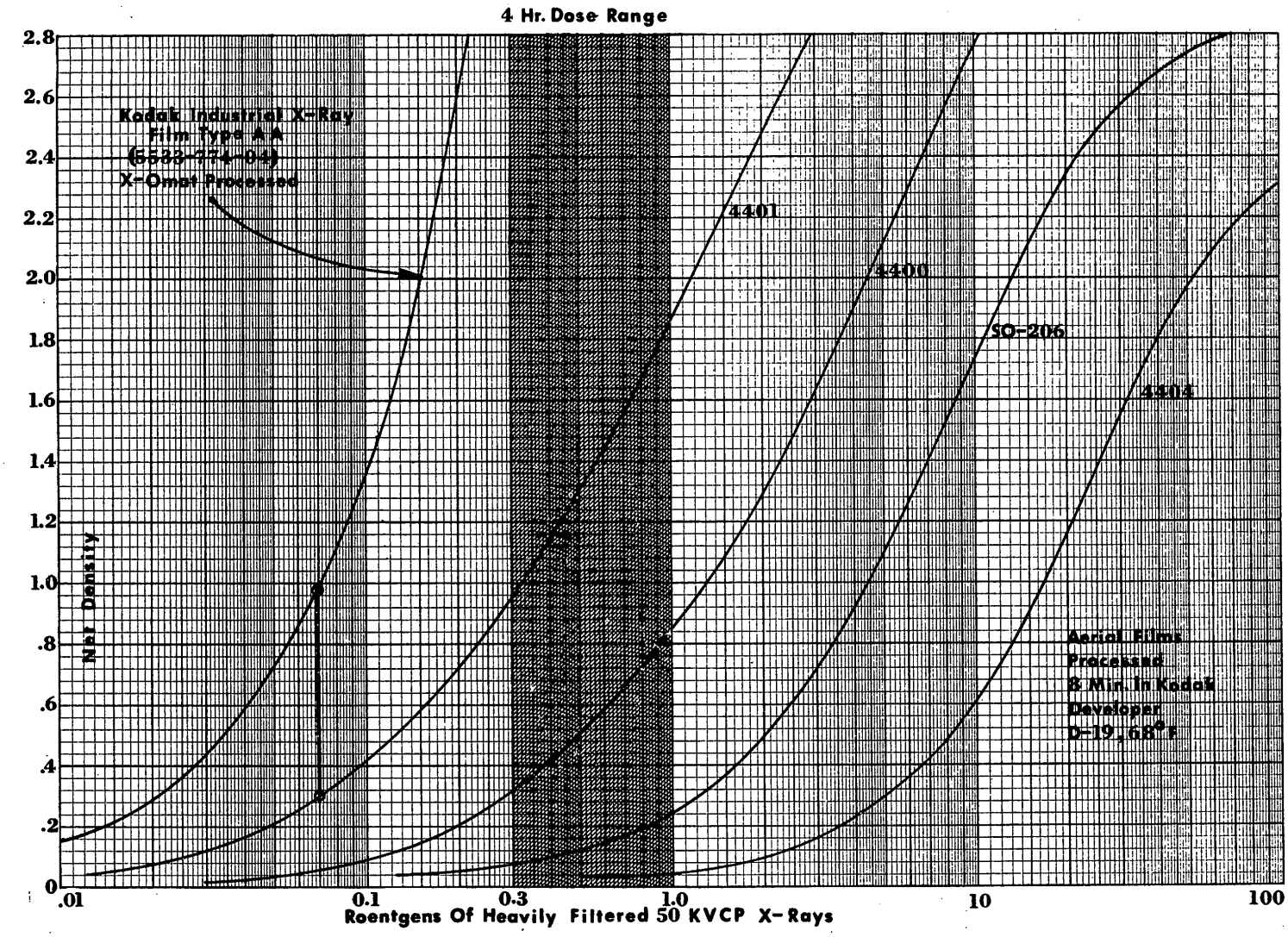

FIG. 5

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